Energy, Mines and Resources Canada | Énergie, Mines et Ressources Canada

CANMET

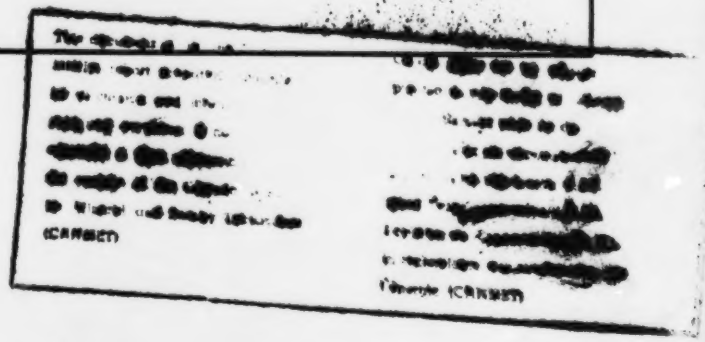
Canada Centre for Mineral and Energy Technology | Centre canadien de la technologie des minéraux et de l'énergie

ALKALI ACTIVATED GROUND GRANULATED BLAST-FURNACE SLAG CONCRETE: PRELIMINARY INVESTIGATION

E. Douglas, A. Bilodeau and V.M. Malhotra
Mineral Processing Laboratory

J. Brandstetr
Technical University, Brno, Czechoslovakia

December 1989



Project: 30.37.01
Use of Supplementary Cementing Materials in Concrete

MINERAL SCIENCES LABORATORIES
DIVISION REPORT MSL 89-135 (IR)

14 pp

MICROMEDIA

90-02558/

ALKALI ACTIVATED GROUND GRANULATED BLAST-FURNACE SLAG CONCRETE: PRELIMINARY INVESTIGATION

by

E. Douglas*, A. Bilodeau**, J. Brandstetr+
and V.M. Malhotra***

ABSTRACT

This report presents results of a preliminary investigation dealing with the compressive strength development of alkali activated ground granulated blast-furnace slag concretes. These concretes incorporated sodium silicate as an activator but did not contain any portland cement. The five concrete mixtures studied were proportioned using sodium silicate and small amounts of hydrated lime. The water-to-binder ratio of the mixtures ranged from 0.34 to 0.50. The air-entrained concrete produced satisfactory workability. The 1-day and 28-day compressive strengths of the concretes ranged from 20.4 to 38.9 MPa and from 45.5 to 59.6 MPa, respectively. The 7- and 14-day flexural strengths were of the order of 5 MPa.

Keywords: alkali activation, ground granulated blast-furnace slag, sodium silicate

---

*Research Scientist, **Engineer, ***Head, Concrete Technology Section, Mineral Sciences Laboratories, CANMET, Energy, Mines and Resources Canada, Ottawa, Ontario, K1A 0G1.
+Professor, Technical University, Department of Technology, Brno, Czechoslovakia.

BÉTON DE LAITIER GRANULÉ ET BROYÉ DE HAUT-FOURNEAU ACTIVÉ AUX ALCALIS : ÉTUDE PRÉLIMINAIRE

par

E. Douglas*, A. Bilodeau**, J. Brandstetr+

et V.M. Malhotra***

RÉSUMÉ

Ce rapport présente les résultats d'une étude préliminaire sur le développement de la résistance en compression de bétons de laitier granulé et broyé de haut-fourneau activé aux alcalis. Ces bétons incorporaient du silicate de sodium en tant qu'activateur mais ne contenaient pas de ciment portland. Les cinq mélanges de béton étudiés furent fabriqués en utilisant du silicate de sodium et de petites quantités de chaux hydratée. Le rapport eau-liant des mélanges variait de 0,34 à 0,50. Le béton à air-entrainé a démontré une bonne maniabilité. Les résistances en compression des bétons variaient de 20,4 à 38,9 MPa à 1 jour et de 45,5 à 59,6 MPa à 28 jours. Les résistances en flexion à 7 et 14 jours étaient de l'ordre de 5 MPa.

Mots-clés: activation aux alcalis, laitier granulé et broyé de haut-fourneau, silicate de sodium

---

*Chercheur scientifique, **Ingénieur, ***Chef, section de la technologie du béton, Laboratoires des sciences minérales, CANMET, Énergie, Mines et Ressources Canada, Ottawa (Ontario), K1A 0G1.

+Professeur, Université Technique, Département de la technologie, Brno, Tchécoslovaquie.

INTRODUCTION

Ground granulated blast-furnace slags possess some hydraulic properties; therefore when slag mortars are made according to current standards, strength development occurs but at a lower rate than in portland cement mortars (1).

It has been established that ground granulated blast-furnace slag mortars and concretes can be activated with alkaline reagents (NaOH, $Ca(OH)_2$, sodium or potassium silicates), yielding compressive strengths comparable to or higher than those made with portland cement alone (2). This opens the possibility of formulating slag concretes without portland cement and possibly with improved properties such as higher resistance to chemical attack (3,4,5,6). This preliminary study presents the proportioning and the properties of five slag concrete mixtures activated with sodium silicate. The work was performed at CANMET laboratories in October 1989.

SCOPE OF INVESTIGATION

Five alkali activated slag concrete mixtures were made. The first three mixtures were made using a sodium silicate solution having a silicate modulus Ms = 1.47 and low water-to-binder* ratios ranging from 0.34 to 0.39. Two other mixtures incorporated a sodium silicate solution of Ms = 1.36 and had higher water-to-binder ratios of 0.50 and 0.46. One of these mixtures was air-entrained.

A number of 102 x 203-mm cylinders and 76 x 102 x 406-mm prisms were cast for compressive and flexural strength testing at various ages.

---

*The binder includes ground granulated slag, solid components of the sodium silicate solution and calcium hydroxide.

CONCRETE MIXTURES

Materials

The concrete mixtures were made in the CANMET laboratory in October 1989 using the following materials:

Slag -- A ground granulated blast-furnace slag from northern Ontario was used in all the mixtures. The chemical composition, glass content and fineness of the slag are shown in Table 1.

Sodium silicate -- Sodium silicate with the following characteristics was used to prepare the solutions added to the concrete mixtures: specific gravity = 1.460 kg/m^3, SiO_2 = 29.73%, Na_2O = 10.78% and silicate modulus Ms = 2.85.

Lime -- Hydrated lime of commercial grade was used in all mixtures to control the setting.

Aggregates -- The coarse aggregate used was crushed limestone with a maximum size of 19-mm and the fine aggregate was natural sand. The grading and physical properties of both the fine and coarse aggregates are shown in Tables 2 and 3.

Air-entraining admixture -- A sulphonated hydrocarbon type air-entraining admixture was used in one mixture.

Mixture Proportioning

In all the mixtures the dry aggregates, the slag, the lime slurry and the water were mixed for two minutes before adding the sodium silicate solution. The lime slurry was constituted by equal parts of hydrated lime and water. The sodium silicate solution of Ms = 1.47 used in mixtures 1, 2 and 3 was prepared with the sodium silicate of Ms = 2.85 of commercial grade by adding a solution of 50% NaOH and water (Table 4). The sodium silicate solution obtained contained 14.77% SiO_2 and

10.48% Na_2O. The SiO_2 and Na_2O content in the sodium silicate solutions was determined by titration with 2N HCl using methyl red as indicator.

The percentage of Na_2O with respect to the slag in the concrete mixtures 1 and 2 was 3.63% and the binder-to-aggregate ratio was 1:3. To make the concrete more cost effective, mixture 3 was proportioned with a binder to aggregate ratio of 1:6. The percentage of Na_2O with respect to the slag in the concrete mixture was 3.41%.

To improve workability in the leaner mixtures 4 and 5, a sodium silicate solution of Ms = 1.36 was prepared with the sodium silicate of commercial grade by addition of 50% NaOH solution and water (Table 5). The binder to aggregate ratio in these mixtures was approximately 1:6 and the percentage of Na_2O with respect to the slag was 6% in both mixtures. The effect of higher contents of Na_2O with respect to the slag in earlier hydration and higher compressive strengths has been discussed elsewhere (2). Nevertheless, in the concrete mixtures studied, the higher water-to-binder ratios in mixtures 4 and 5 results in lower strengths than in mixtures 1, 2 and 3 in spite of the higher Na_2O to slag ratio. The grading of the aggregate was the same as the one used for mixtures 1, 2 and 3 but 6.5% of the total aggregate was fine sand passing 150 μm and added as a filler (Table 2).

The proportions of mixtures 1, 2 and 3 are shown in Table 4 and those of mixtures 4 and 5 are shown in Table 5. An air-entraining admixture was added in mixture 5.

PREPARATION AND CASTING OF TEST SPECIMENS

A number of 102 x 203-mm cylinders were cast to determine compressive strengths up to one year and prisms were cast for testing in flexure at 7 and 14 days in mixtures 1 and 2, and at 14 days in mixtures 4 and 5. All cylinders and prisms were

cast in two layers, each layer being compacted using a vibrating table.

After casting, all the moulded specimens were covered with water saturated burlap and left in the casting room at 23 ± 1.7°C for 24 h. The cylinders were then demoulded and after density measurements they were transferred to the moist curing room until required for testing.

TEST RESULTS

Properties of freshly-mixed concrete are given in Table 4 for mixtures 1, 2 and 3, and in Table 5 for mixtures 4 and 5. The slump of concrete as a function of time after mixing for mixtures 4 and 5 is shown in Table 6.

Compressive and flexural strengths test results are given in Table 7.

DISCUSSION OF TEST RESULTS

As shown in Table 4, mixtures 1 and 2 with a binder to aggregate ratio of 1:3 had a higher content of ground granulated blast-furnace slag requiring the addition of high amounts of sodium silicate and thus rendering the mixtures too costly. It has to be noted that mixture 1, with a water/binder = 0.39 had a slump of 165 mm, while mixture 2, with a water/binder = 0.34 was not workable. The leaner mixture 3, with a binder to aggregate ratio of 1:6 and a water/binder = 0.35 also had no slump. The lack of workability in mixtures 2 and 3 was probably due to the lower water-to-binder ratios.

High compressive strengths were obtained at all ages in concrete mixtures 1 and 2. The leaner concrete mixture 3 performed better than concretes from mixtures 1 and 2 although the Na_2O to slag ratio was slightly lower. This fact cannot be easily explained. The flexural strengths of concretes from mixtures 1 and 2 at 14 days were slightly lower than at 7 days.

An air-entraining admixture was incorporated in mixture 5 to obtain an air content of 4.2 per cent. Slump was measured in mixtures 4 and 5 as a function of time and, as shown in Table 6; the slump retention was good even after 45 minutes, that is, the slump at 45 minutes was 100 mm and 70 mm for mixtures 4 and 5, respectively, compared to a slump of 140 mm measured 13 minutes after adding the sodium silicate to the mix. Table 8 shows that compressive strengths approaching 45 MPa at 28 days were obtained for both concretes. The values of compressive and flexural strengths of concretes from mixtures 4 and 5 were similar regardless of the difference in water to binder ratios. This may be explained partly by the higher air content of mixture 5.

CONCLUDING REMARKS

1. Ground granulated blast-furnace slag activated with sodium silicate can be used to make slag concretes with satisfactory workability and strength properties at ages up to 28 days.

2. For the binder-to-aggregate ratios of approximately 1:6, the amount of sodium silicate of Ms = 1.36 added should be such to maintain a percentage of Na_2O with respect to the slag of approximately 6%.

3. A 1:1 lime slurry should be added as a retarder in a proportion of approximately 4% $Ca(OH)_2$ with respect to the slag.

4. Air can be entrained in activated slag concrete in order to improve workability and durability.

REFERENCES

1. Douglas, E., Elola, A. and Malhotra, V.M. "Characterization of ground granulated blast-furnace slags and fly ashes and their hydration in portland cement blends"; In print, ASTM Cement, Concrete and Aggregates, Vol. 12, No. 2, Summer 1990.

2. Douglas, E. and Brandstetr, J. "A preliminary study on the alkali activation of ground granulated blast-furnace slag"; MSL Report 88-135, pp. 16; 1988.

3. Glukhovsky, V.D., Krivenko, P.V., Rostovskaya, G.S., Timkovich, V.J. and Pankratov, V.L. U.S. Patent No. 4, 410, 365; 1983.

4. Voinovitch, J.A. and Dron, R. "Effect of various activators on the hydration of granulated slag"; Silicates Industriels 41:209-212; 1976.

5. Talling, B. and Brandstetr, J. "Present state and future of alkali-activated slag concretes"; Proceedings of the Third International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete"; Trondheim, Norway, June 18-23, 1989; pp. 1519-1545; ACI SP-114, V 2, V.M. Malhotra, Editor, 1989.

6. Glukhovsky, V.D. et al. "High strength slag-alkali cements"; Seventh International Congress on the Chemistry of Cement V/164-168; Paris; 1980.

Table 1 - Physical properties and chemical analysis of the granulated blast-furnace slag

Description of Test		Slag
Fineness		
Passing, 45 μm		97
Surface area, Blaine, m^2/kg		460
Chemical analysis		
SiO_2		38.00
Al_2O_3		8.74
Fe_2O_3		0.55
CaO		32.00
MgO		18.60
SO_3		2.45
K_2O		0.76
Na_2O		0.22
Loss on ignition		1.98
Glass content		90.3
Compressive strength of mortars (50% PC) ASTM C 989	7 days	18.7
	28 days	31.4
Slag activity index, % (ASTM C 989)	7 days	69.8
	28 days	100.0

Table 2 - Grading of Aggregates

Coarse Aggregate		Fine Aggregate		
Sieve Size	Cumulative Percentage Retained	Sieve Size	Cumulative Percentage Retained	
			Mix 1, 2 and 3	Mix 4 and 5
19.0 mm	0.0	4.75 mm (No. 4)	0.0	0.0
12.7 mm	35.0	2.36 mm (No. 8)	10.0	8.5
9.5 mm	60.0	1.18 mm (No. 16)	32.5	28.0
4.75 mm	100.0	600 μm (No. 30)	57.5	49.5
		300 μm (No. 50)	80.0	68.5
		150 μm (No. 100)	94.0	80.5
		pan	100.0	100.0

Table 3 - Physical Properties of Aggregates

	Coarse Aggregate*	Fine Aggregate**
Specific Gravity	2.69	2.70
Absorption, %	0.82	1.1

*Crushed limestone
**Natural sand

Table 4 - Mixture Proportions and Properties of Fresh Concrete - Mixtures 1, 2 and 3

	Mix No.	1	2	3
Mix Proportions per m^3	Fine Agg.	523 kg	530 kg	819 kg
	Coarse Agg.	1042 kg	1057 kg	1143 kg
	Water	63 kg	40 kg	28 kg
	Lime slurry*	26 kg	33 kg	23 kg
	Slag	517 kg	524 kg	324 kg
	Na-Silicate sol.**	201 kg	203 kg	128 kg
	Water/binder	0.39	0.34	0.35
Properties of Fresh Concrete	Slump (mm)	165	0	0

*Lime slurry: 50% lime, 50% water by weight

**Specific gravity of solution = 1.34

For 1 Liter of solution: 449 mL of sodium silicate of Ms = 2.85
143 mL of NaOH 50%
408 mL of water

Analysis of sodium silicate solution: 14.77% SiO_2
10.48% Na_2O
Ms = 1.47

Table 5 - Mixture Proportions and Properties of Fresh Concrete - Mixtures 4 and 5

	Mix No.	4	5
Mix Proportions per m^3	Sand	747 kg	745 kg
	Coarse Agg.	1044 kg	1038 kg
	Fine sand (filler)	125 kg	124 kg
	Water	58 kg	43 kg
	Lime slurry*	23 kg	23 kg
	Slag	271 kg	269 kg
	Na-silicate sol.**	129 kg	129 kg
	Air-entr. agent	0	245 mL
	Water/binder	0.50	0.46
Properties of Fresh Concrete	Unit Weight	2395 kg/m^3	2370 kg/m^3
	Slump	140 mm	140 mm
	Air	2.2%	4.2%

*Lime slurry: 11.5 kg of Lime + 11.5 kg of water
**129 kg of sodium silicate solution = 97.5 litres
For 97.5 L of sodium silicate sol.: 54.3 L of sodium silicate sol. of Ms = 2.85
18.5 L of NaOH 50%
24.7 L of water
Analysis of sodium silicate sol.: 12.77% Na_2O, 16.82% SiO_2, Ms = 1.36

Table 6 - Workability of Concrete vs. Time After Mixing

Concrete 4		Concrete 5	
Time (min)	Slump (mm)	Time (min)	Slump (mm)
0*	-	0*	-
13	140	5	140
23	115	15	120
43	100	30	70
65	95	50	75
103	30	75	50
138	20	105	45
		125	25

0 = when sodium silicate solution was added to the mix

Table 7 - Properties of Hardened Concretes

Mix No.	W/binder	Density of Cylinders (kg/m^3)	Compressive Strength (MPa)					Flexural Strength (MPa)	
			1d	3d	7d	14d	28d	7d	14d
1	0.39	2373	28.1	38.2	41.6	43.4	46.3	5.3	4.8
2	0.34	2387	37.5	41.8	44.6	48.3	51.0	5.8	5.5
3	0.35	2464	38.9	49.4	54.5	-	59.6	-	-
4	0.50	2435	23.2	33.7	41.0	43.1	45.4	-	6.3
5	0.46	2415	20.4	35.0	41.5	44.3	46.8	-	6.3